Invited Paper

Excimer Laser as a Total Light Source Solution for DUV Microlithography

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ABSTRACT

Excimer lasers are now being used in the manufacturing of ultra-large scale integrated devices that require feature widths of less than 0.25µm. The excimer laser for microlithography, since its introduction in 1987 has evolved from a laboratory instrument to a manufacturing tool. We will trace the history of the excimer laser in this industry and explain why it is and remains the total solution for the present and for many years in the future.

Keywords: Excimer laser, Deep Ultraviolet Microlithography, KrF, ArF, F_2, Hg lamp

1. INTRODUCTION

By 1996, the transition from an I-line (365nm) mercury lamp to deep-UV excimer laser – KrF (248nm) – as the illumination source for fabrication of ULSI had begun in earnest. The rapid transition is considered evolutionary and revolutionary. Evolutionary because the change in technology in the eyes of the IC maker was a mere reduction in UV wavelength. Revolutionary because of the complexity and the pulsed operation of the laser compared with the simple and continuous Hg lamp. However, we show that excimer lasers are optimally suited to meet the requirements for Deep-Ultraviolet microlithography as compared to Hg lamps at 248nm or solid state lasers at deep-ultraviolet wavelengths. The physics of excimer laser allows scaling to higher powers, narrower spectral widths and shorter wavelengths. The engineering of excimer lasers has kept pace with microlithography scanner requirements. New excimer products have maintained the performance trends set-up by the previous generation excimer products. In laboratory experiments, solid state lasers have shown promise. However, the scaling of a solid state to higher powers is still several years away, and has missed the opportunity to play a role in this very important semiconductor industry.

2. MICROLITHOGRAPHY – THE PROCESS

2.1 What is microlithography

Microlithography is a manufacturing process for highly precise microscopic 2-D patterns in a photosensitive resist material. These patterns are replicas of a master pattern on a mask, which is made from patterned layer of chromium on fused silica. At the end of the lithographic process, the resist is used to create a useful structure in the device that is being built such as trenches on silicon wafer (Fig. 1) or metal network on silicon. These structures then form the foundation for memory and processor chips that go into computers, cellular phones, PDAs, cars and about everything else. Microlithography is the technology and cost driver for semiconductor manufacturing.

2.2 Microlithography and microelectronics explosion

Progress is microlithography is evident due to continuous decrease in image sizes (Figures 1 and 2). A decrease in image size by X2 leads to a X4 increase in number of circuits per unit area, and significant improvements in switching speeds. Thus, a decrease in transistor size, and increase in chip size has resulted in rapid growth of number of transistors per chip. About half of the 4X increase per generation in DRAM capacity is due to reduced image size. The rest is from advances in design and increase in physical

dimensions. Historically, it has taken about three years to advance from one generation of DRAM to the next. However, leading-edge microlithography started at 0.35mm in 1995.

2.3 The path to narrower images

Image Dimension is governed by Rayleigh's formula:

$$D = k1*\lambda/NA, \quad (1)$$

Where
D = Minimum Dimension printed on wafer, k1 = process constant, between 0.6 to 0.8,
λ = Exposure Wavelength and NA = Numerical Aperture Of Lens (Fig. 3)

Thus, increasing NA may minimize the image dimension. But, the Depth of Focus (DOF) is related to NA via:

$$DOF = \pm k2*\lambda/NA^2, \quad (2)$$

Where:
k2 = process constant, ~ 0.5.
Despite DOF issues, increasing NA from 0.5 to 0.7 in the past few years (Fig. 4) has reduced image dimensions. By far, though, the greatest reduction in image size is achieved by reducing the wavelength. This is exactly where excimer lasers fit in!

3. MICROLITHOGRAPHY – THE ROLE OF LASERS

3.1 Excimer lasers and solid state lasers

Traditional light source for lithography has been Hg-Xe Arc Lamps. Its i line and g line are used for lithography below 256MB DRAM. Its emission centered on 248nm has also been used, but power is very low. On the other hand, excimer lasers, KrF at 248nm and ArF at 193 nm and F2 lasers at 157nm are sources of high power radiation. They have relatively narrow spectrum - thus optical filtering is not required. They provide tunable high power output at DUV, without wavelength conversion. They may be directly, efficiently spectral narrowed without external "injection" lasers. **Most importantly**, excimer lasers would act as sources for three generations of DRAM, at 248, 193 and then 157nm. They can be scaled in power and spectrally narrowed for the future microlithography. Excimer lasers are expected to meet the lithography requirements for 16Gbit DRAM and 10GHz microprocessors in the next ten years!

Solid State Lasers are other possible sources. Some examples are Alexandrite at 248 nm, and diode pumped lasers at 248 and 193 nm. But, considering the early lead by excimer lasers, it is **just too late** for solid state lasers!

3.2 Lasers and the microlithography process

The wafer exposure process involves the following systems: Laser, relay optics, homogenizer, illumination systems, lithography projection lens and wafer positioning system (Fig. 5). In terms of complexity, the lens is the most complex, the laser is the second most and the positioning system is the third.

The lithography projection lens is a large compound lens made up of over 20 simple elements mounted in a rigid barrel. The large number of elements corrects optical aberrations over a 30mm exposure field. The wavefront aberration must be less than $\lambda/10$ at every point in the exposure field. This lens produces the optical image of the mask, reduced by a factor of 4 or 5. A silicon wafer is exposed to this image, which is captured by the layer of photoresists. This image is eventually developed to leave the resist pattern on silicon. The lens at 248nm is not chromatically corrected. Hence, the narrow spectral width requirements. Thus for a lens of NA=0.7, the Full-Width-At-Half maximum requirement is about 0.6pm. At 193nm, there is some color correction otherwise the linewidths requirements are very low. The situation at 157nm is still

open. At 248nm, the lens material is fused silica, at 193nm is mostly fused silica and CaF2 and at 157nm it will be very likely CaF2.

The wafer positioning system is probably the most precise mechanical system in existence. It positions the wafer (200mm in diameter) under the lens by stepping or scanning to a precision of better than 20nm. The motion of the wafer positioning system coupled with the exposure technique determines two classes of microlithography systems - stepper and scanner.

Stepper exposes one chip at a time. The number of pulses the laser fires on each chip is equal to the total energy required to expose the resist. After each chip, the wafer positioning system moves the wafer to next. The field size depends on the lithography lens diameter. A scanner exposes the chip by painting a slit over the wafer. This is done by scanning the mask and the wafer through the slit. The field size is then limited by slit height and scan length. Since the slit is much smaller than the field size, the optical constraints on the litho lens are greatly reduced. Thus, all lithography equipment manufacturers have now switched to the design & development of scanner technology.

3.3 Impact of scanner based microlithography on laser performance

The scanner fundamental formula is given by:

$$\text{Time to expose the scanner slit} = s/V\text{scan}, \qquad (1)$$

where s is the slit width (typically 7 to 8mm wide) and Vscan is the scan speed of the scanner (100 to 250mm/sec). The time each point is within the slit should be at least equal to the time required to fire N pulses to expose the resist. Thus, if the resist requires Dr mJ/cm^2, and the laser provides $D_L mJ/cm^2$ per pulse, the number of pulses required to expose the resist is Dr/D_L. Thus, for a laser with repetition rate of f, the time to expose Dr/D_L pulses is just $Dr/ D_L /f$. The goal of every litho equipment maker is to minimize exposure time. Thus, the laser **repetition-rate** must be maximized. The lithography process requires that the whole chip must be exposed uniformly. This means the energy of the laser, integrated over the exposure time must be constant. This forms the basis of **dose stability** requirement of the laser!

Excimer lasers today (20W KrF, 10W ArF) has kept up with scanner power requirements (Fig. 6). The "physics" allows scaling to higher powers without scaling laser physical size. In fact, the laser chambers used in CX2 product and ELS-6000 product have similar physical dimensions.

The "homogeneously" broadened KrF and ArF laser lines can be narrowed to 0.5pm FWHM at 248 and 193 nm without much loss in efficiency (Fig. 7). The line narrowing module used in first generation product and next generation product have similar physical dimensions.

Power stability of excimer laser is measured by the stability of the dose (integrated energy). Scaling the power of excimer laser without maintaining its stability will not help lithography. Power stability can be maintained by a combination of gas flow, pulsed power and software control technology.

The cost-of-operating a laser depends heavily on chamber life (~40% is due to chamber). The pulse life of a chamber has steadily improved, resulting in a huge decrease in cost-of-operation of the laser. While the cost-of-operation may not be as low as a Hg lamp, the reduction in past several years has been encouraging at 248nm. Similar improvements are required at 193nm.

A mix-and-match strategy will be followed by the chipmakers in integrating laser-based tools for lithography. For 256Mbit DRAM, approximately 70% of the layers would be exposed via Hg iline and the remaining via KrF. For 4Gbit DRAM, approximately 40% layers would use iline, 40% KrF and 20% ArF. Such mix-and-match strategy would keep iline technology alive. Likewise, this mix-and-match would keep excimer lasers arrive when microlithography reverts to EUV and E-beams.

4. MICROLITHOGRAPHY – FUTURE OF EXCIMER LASERS

The physics of excimer laser allows scaling to higher powers, narrower spectral widths and shorter wavelengths. Excimer lasers would provide a three-generation solution to microlithography. The engineering of excimer lasers has kept pace with stepper/scanner requirements of cost-of-operation, uptime and reliability. New excimer products have maintained the performance trends set-up by the previous generation excimer products. The economics has driven and will continue to drive the direction of microlithography. Excimer lasers have kept pace with that. This explains why a small excimer laser company in San Diego has experienced such rapid growth.

ACKNOWLEDGEMENTS

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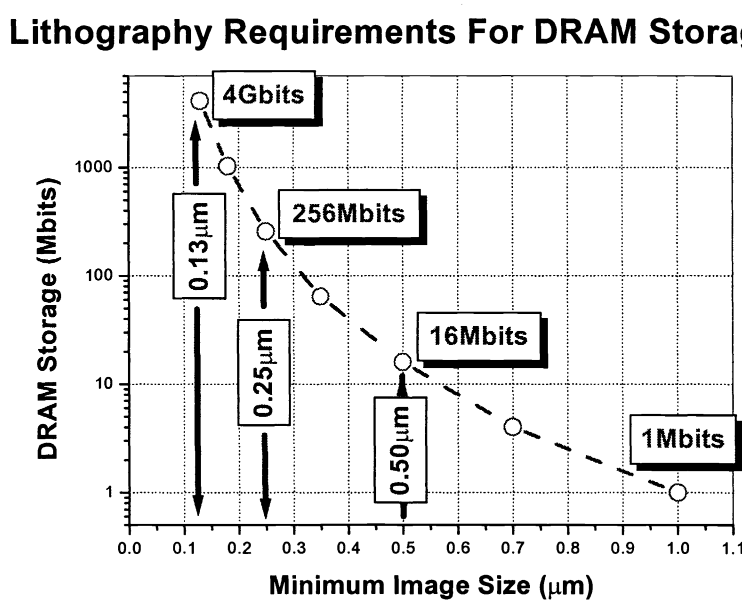

Figure 1. The increased DRAM capacity is associated with decreased image size

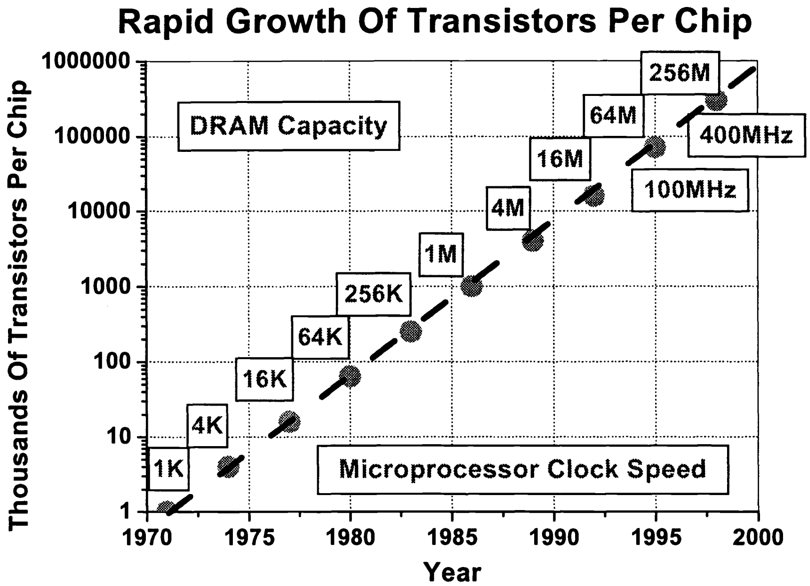

Figure 2. The relative increase in number of transistors per DRAM keeps pace with the increase in DRAM capacity.

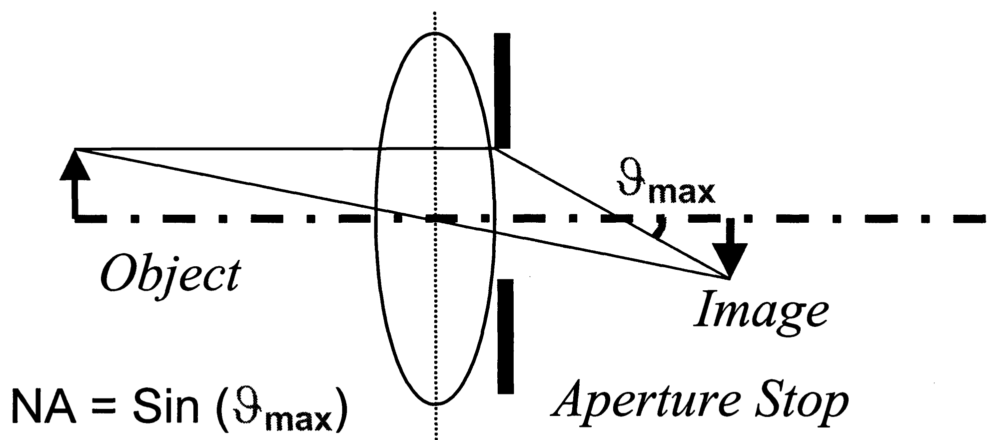

Figure 3. The properties that determine lens NA.

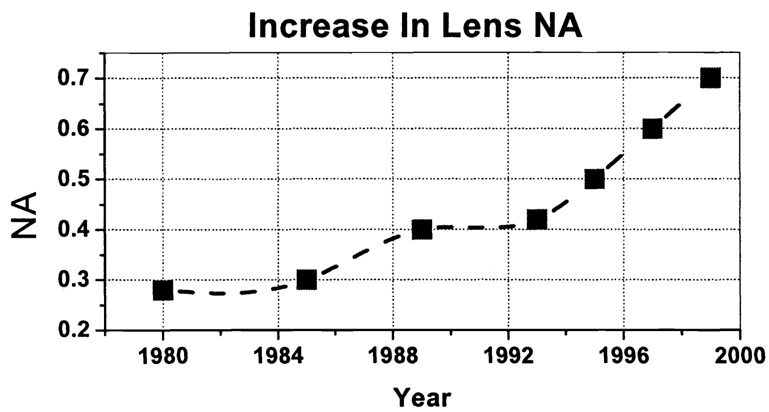

Figure 4. Lens NA has more than doubled in the past 20 years.

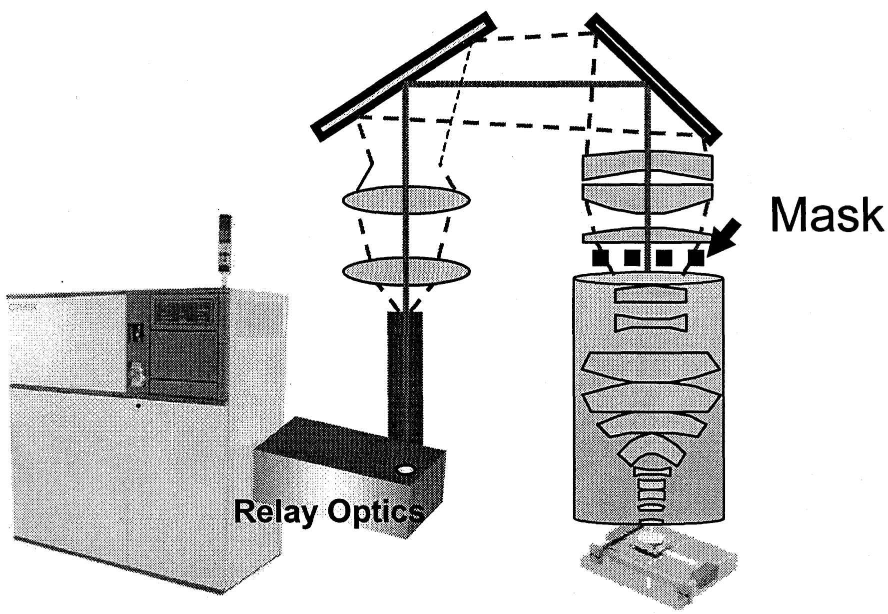

Figure 5. A laser based microlithography exposure system.

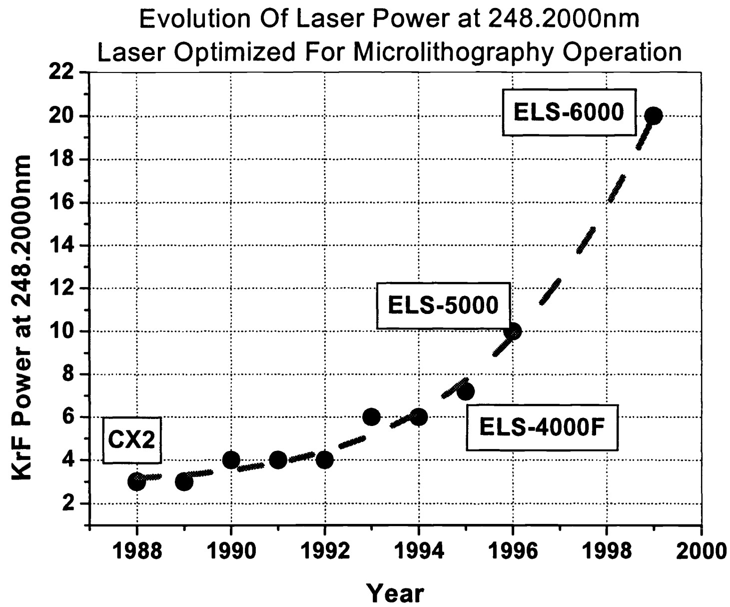

Figure 6. The evolution of laser power during the past ten years has kept up with scanner requirements.

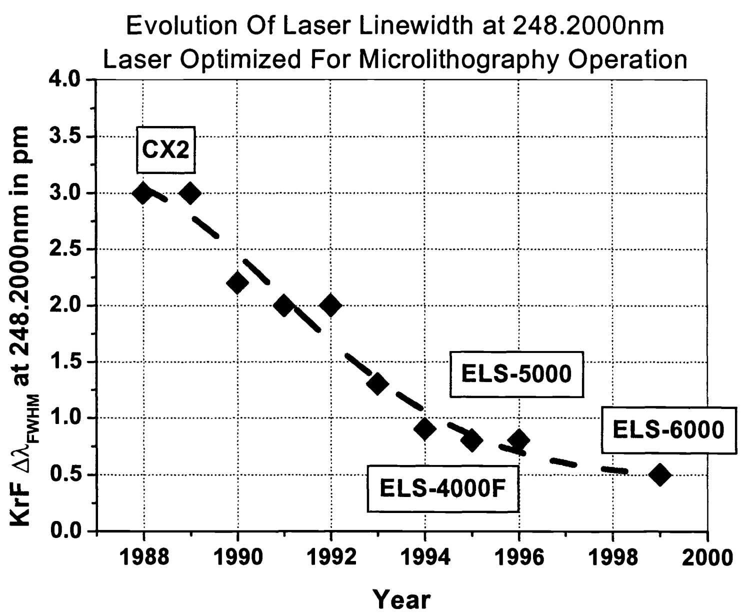

Figure 7. The decrease in linewidth in the past ten years has kept up with the lens requirements.